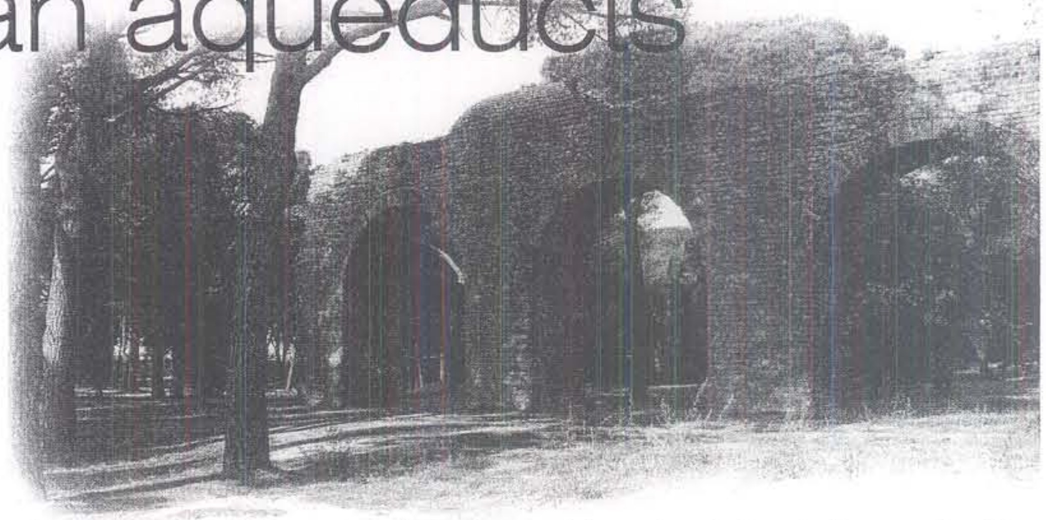
Facts and fables of Roman aqueducts



The aqueduct at Fréjus in Provence in south-east France carried water from the Siagnole River more than 37 km to what was a Roman seaport in the first century AD. These are the arches de Sainte Croix.

We might think that Roman aqueducts and other hydraulics structures of that era are old hat — long superseded by computer predictions and complex modern arithmetic. But we would be wrong, according to Hubert Chanson* who believes Roman hydraulic engineers knew far more than their current day counterparts.

Roman aqueducts supplied water to cities for public baths and sewerage systems as well as public fountains. They were long subterranean conduits, following contour lines, with flat longitudinal slopes (1 to 3 m per km, even less at Nimes — 0.24 m/km).

Numerous aqueducts were used for centuries and some are still in use (eg, at Carthage, Mons). Their construction was a huge task, often performed by the army under the guidance of military hydraulic engineers.

Their cost was extraordinary considering the real flow rate (ie, less than 400 L/s) — about 1 to 3 million sesterces per kilometre. This is the equivalent of about US$20 to 60 million per kilometre today. For comparison, the construction of the Tarong water pipeline in Queensland cost about US$100,000 per km in 1994.

I am very impressed by the hydraulic knowledge, experience and expertise of the Roman engineers. They knew much more than most modern hydraulic engineers — yet we still know so little of their background.

Hydrology of Roman aqueducts

The hydrology of some catchment areas supplying Roman aqueducts has been investigated at several locations in France. For example, the 'source de l'Eure' at Uzes supplying the Nimes aqueduct, the 'source de Gorze' feeding the Gorze aqueduct (Metz), the 'source du Thou' and 'ruisseau d'Arches' supplying the Mont d'Or aqueduct (Lyon) and the 'sources de la Siagnole' feeding the Mons aqueduct (Frejus).

Dynamic flow regulation is commonly used in modern times and it involves a series of operations to respond constantly to user demand.

Part of the Nimes aqueduct, this pier the Pont de Bordnègre is shaped to cut the impact of water flow.

All are still in use. At Uzes, the catchment area was about 45 km^2. Flow rate measurements show an average daily discharge of about 29,600 m^3/day, with maximum daily flow of 143,400 m^3/day and minimum daily output of 10,800 m^3/day.

At Gorze, the catchment area was 58 km^2 with an average daily source flow rate of 8050 m^3/day, with maximum flow rate of about 11,000 m^3/day and minimum daily flow rate of less than 1100 m^3/day.

At Mons the average daily flow was 97,200 m^3/day, with a maximum daily output of 1,550,000 m^3/day and a minimum daily flow of zero (dry).

For the Mont-d'Or aqueduct, modern data suggest an average daily flow of 1400 m^3/day, with daily minimum and maximum of 250 and 4500 m^3/day.

Overall, recent hydrological data show large variations in stream flows. During dry periods, the daily flow was typically less than 10% of the maximum discharge.

While the flow rates during Roman times are unknown, it is plausible that hydrological variations were similar to present trends. This suggests that the aqueducts conveyed relatively low flows during dry periods.

Regulation basins

Several aqueducts were equipped with regulation basins installed along the canal. Most of these were equipped with a series of gates and an overflow system.

Basic hydraulic considerations imply that undershoot gates were used to regulate the aqueduct flow while overshoot gates were used for the overflow discharge.

Hydraulic calculations were conducted for two large regulation basins on the Gorze and Nimes aqueducts. The results demonstrated that the undershoot gate openings had to be small ie, between two and 10 cm at Gorze, and between three and 12 cm at Nimes.

This type of operation implied fine gate opening adjustment systems to enable precise flow regulation.

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What type of flow regulation?

Water supply operation can be based on two different techniques — on/off (ie, 100% or 0%), or a dynamic flow regulation. In the former case, the gates were open constantly and the water flowed to the cities, without regulation other than the force balance between gravity and flow resistance.

The gates and valves were used to stop the flow for repairs, maintenance and cleaning. Dynamic flow regulation is commonly used in modern times and it involves a series of operations to respond constantly to user demand.

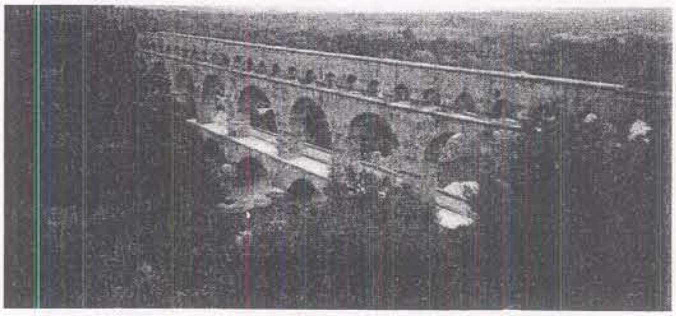
In Roman times, this type of operation would have required an engineer in charge of the regulation, gangs of workmen operating the gates and a good communications system along the aqueduct canal.

Dropshaft cascades

Although most aqueducts had a mild slope there were also some steep sections. Three designs of steep sections were commonly used: ie, smooth steep chute, stepped chute and cascade of dropshafts.

The latter is most unusual, even in modern times.

A dropshaft is a vertical shaft connecting two canals at different heights. Such a structure is commonly used in sewer systems today. A dropshaft is an energy dissipator.



The Pont du Gard is 21 km north-east of Nimes in southern France and served as a bridge across the River Gard for chariots and pedestrians as well as water. Built around 19 BC, the Pont du Gard is about 49 m high and 27 m long. Part of the 50 km Nimes aqueduct, the Pont du Gard was built of uncemented local stone. This view is from the right bank of the River Gard.

Roman dropshafts were characterised by a deep pool and a relatively wide shaft, compared with modern designs. A recent study showed that the Roman dropshaft design was most efficient.

The Roman hydraulic and civil engineers also devised cascades of dropshafts, ie, a succession of dropshafts installed inline.

The construction of a dropshaft cascade was a very difficult task, with numerous subterranean conduits, connected by vertical shafts, in a steep topography (eg, Valdepuentes).

Even in modern times, the task would be a major engineering challenge. The successful operation of dropshaft cascades for centuries demonstrates sound design and a solid hydraulic experience, if not expertise.

Recently, some hydraulic studies of Roman dropshaft models were conducted in 1/3 scale models and at full-scale. The results highlight a satisfactory dropshaft operation for a wide range of flow conditions and dropshaft geometries, but for a narrow range of discharges.

The latter range may be predicted analytically. Two shapes of dropshafts were typically used — rectangular and circular — for example, circular at Valdepuentes and Cherchell, rectangular at Recret, Vaugneray.

At Valdepuentes, one dropshaft cascade, Fuentes de la Teja-Madinat al Zahra, included three shafts with an outlet canal at 90° with the inlet canal direction. Such a geometry was rare, although there were possibly five shafts with such a disposition at Montjeu (Autun).

It was a very efficient hydraulic design in terms of energy dissipation.

Culverts

A culvert is a short conduit to allow stream flows beneath an embankment. The Roman built a number of culverts beneath major roads as well as beneath aqueducts.

An impressive culvert was the multi-cell box culvert underneath the Nimes aqueduct at Vallon No 6, downstream of Pont du Gard. Unique features of the culvert were a multi-cell design, large size and a modern hydraulic design.

The culvert could handle 4.2 m^3/s, almost 12 times the maximum discharge capacity of the Nimes aqueduct. In the barrel, the flow velocities were about 2.5 m/s for a 3 m^3/s flow rate.

This structure demonstrates that Roman engineers understood hydrology and runoff, and that they had solid hydraulic design experience.

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